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The Impact of Temperatures on the Stability of Rocks Surrounding a Single Fracture

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Abstract. Research on the influence of temperature and the accompanying stress on the stability of the rocks surrounding an underground tunnel has become ever more important. This paper constructs a geometric model of a single-fracture tunnel by combining a high-temperature underground tunnel as the object of study with an example that uses a high-temperature tunnel segment in the water diversion tunnel of a hydropower station in Xinjiang. Based on the relevant theoretical analysis, with the consideration of different working conditions, a numerical experimental analysis was conducted to determine the two-dimensional transient temperature field distribution of the tunnel rock mass by using a numerical analysis software. The experimental data was consistent with the measured data. The calculated results show the following: a. when the temperature difference is greater, the stress concentration is higher near the fracture of the surrounding rock; b. the degree of the stress concentration in the crack tip region is not positively correlated to the distance, and there is a sensitive region where the stress varies.

1. Introduction

At present, regarding the stability of underground tunnel engineering, the effects of temperature are largely ignored. When the rocks surrounding an underground tunnel go through deformation under the action of temperature, the presence of many particles, pores and micro-cracks of low strength within the rocks will result in a large local stress concentration, which thereby induces the formation, development, compaction and interconnection of larger cracks until the entire tunnel becomes unstable and damaged.

The research on high-temperature tunnels is still not fully developed, both domestically and abroad. Reports of a high-ground-temperature phenomenon in the literature can be traced back to the second half of the 19th century. Issues related to high temperatures have occurred diversely in the construction of deep, long tunnels in various countries thereafter. In response to the frequently occurring mechanical behavior of rock under the action of high temperatures, scholars from all over the world have carried out research [1-3]. Dwivedi et al. [4] studied the physical and mechanical properties, permeability and fracture evolution pattern of Indian granite within the temperature range of 30~160℃. The basic equation of solid hydrothermal coupling for saturated fractured rocks was presented for the first time by Noorishad et al. [5]. Li Ning et al. [6] have initiated many valuable research studies; they derived three-field coupling differential equations for saturated and quasi-saturated porous fractured rocks and soil based on Gatmiri's three-field coupling study and constructed the coupling numerical model of rock, fracture, water and gas. The studies above all focus on the

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thermal characteristics of rock or the multi-field coupling constitutive relationship of fractured rock and soil to evaluate the rock stability, which rarely involved the stress and deformation of fracture-containing surrounding rocks under different temperatures; however, this work is particularly important and indispensable for guiding on-site construction. This paper developed a computational model for fracture-containing surrounding rocks at different temperatures by applying a combination of specific engineering with the finite element method of the transient temperature field and analyzed the distribution pattern of the stress field and deformation field for the rock mass surrounding a tunnel, which provides future design and construction with an effective theoretical foundation.

2. Computational model and boundary conditions

The water diversion tunnel of a hydropower station in Xinjiang was selected as the research subject for this paper. The surrounding rocks of the power tunnel construction adits are mainly granite-based. The temperature of the surrounding rock is with an average greater than 30 ℃ and the highest exceeding 80 ℃. The depth of the granite main section in the tunnel is relatively large; thus, a high-temperature phenomenon was evidently present.

The computational model is constructed by selecting a tunnel surface containing a crack as the object of study. The numerical model of the tunnel and the application of the boundary conditions are shown in Figure 1 and Figure 2, and the diameter of the tunnel is D=6 m. According to the symmetry of the structure and load, only one-quarter of the crack length is required in the construction of the model. The length of the crack is a=0.5 m. It is assumed that the crack is a straight strip-shaped slit, the crack width is constant, the crack surface is smooth, and the crack length is far greater than the crack width. Due to the stress concentration that can occur on the crack tip in the meshing division. The network model consists of 1604 units and 1638 nodes. We applied uniform temperature to the entire model to increase the reference temperature and then used a stepped load while applying the constant temperature boundary. Kuna M, Liesk H. [7] noted that the maximum tensile stress occurred on the specimen surface where the thermal shock was received. In addition, the thermal shock is an unstable heat conduction process, the internal temperature of the specimen varies with time, and the stress induced by the thermal shock also varies accordingly. In the process of solving, the Jacobian conjugate gradient iterative equation solver is set as the solution option.

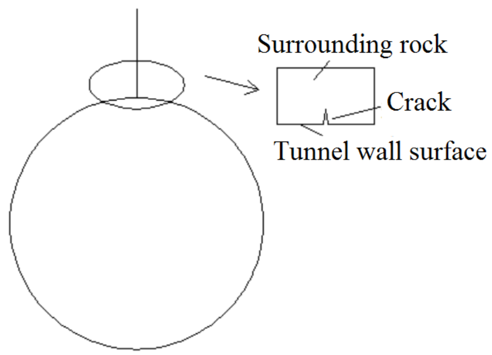

Figure 1. Vertical distribution of cracks on the roof arch and generalized model

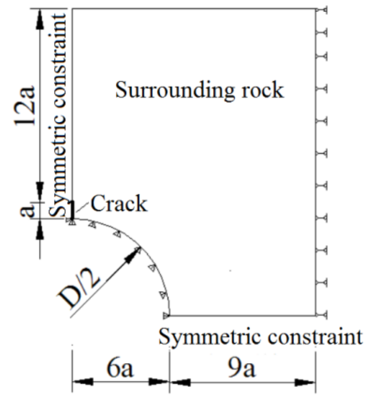

Figure 2. Diagram for the 1/4 Computational model of a crack-containing tunnel and boundary conditions

3. Determination of test plans and parameter selection

To study the influence of different temperatures on the stability of single-fracture surrounding rocks, this paper examined the impact pattern of the temperature in different regions near the fracture by taking various temperatures of surrounding rocks into consideration, starting with the fracture temperature of 5 ℃. The model selects the stress characteristics of the points in different regions to represent the stress received in that region, with the goal of obtaining the transferring pattern between the fracture and the surrounding rock. The numerical experiment selects granite (Ⅳ1 type) as the object. The thermal physical parameters of the material are shown in Table 1.

Table 1. Numerical experiment parameters.

Crack temperature (℃)	Tempe -rature (℃)	Deformation modulus (GPa)	Poisson's ratio	Linear expansion coefficient (10^{-6}℃)	Specific heat (J/kg ℃)	Thermal conductivity Coefficient W/(m·℃)	Bulk weight (kN/m^3)	Depth (m)	Tunnel radius (m)
5	25	4.0	0.21	4.9	760	2.5	27	600	6.0
	60	4.2		5.3		2.4			
	70	4.5		6.2		2.3			
	80	4.7		7.5		2.2			
	90	4.5		8.4		2.1			

4. Determination of test plans and parameter selection

4.1. Numerical experimental analysis

According to the analysis and calculation of the proposed numerical experimental plan, the crack tip is assigned to the origin (0, 0) in the construction of the coordinate system. Select 4 points of different positions in this coordinate system to represent the 4 regions near the fracture.
Select any point A near the crack tip (x=0.187 m, y=0.28 m). Figure 3 shows the temperature variation curve of point A that increases along with time under the influence of temperatures.

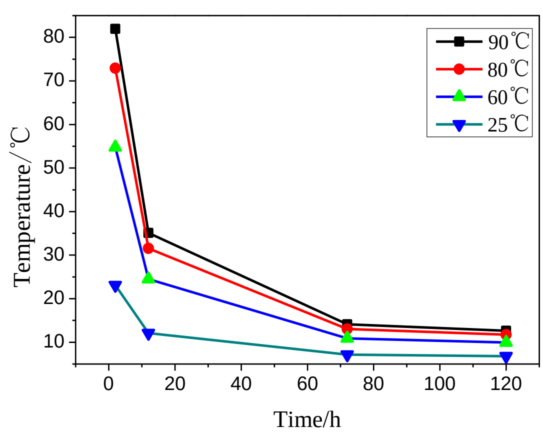

Figure 3. Temperature variation curve of Point A.

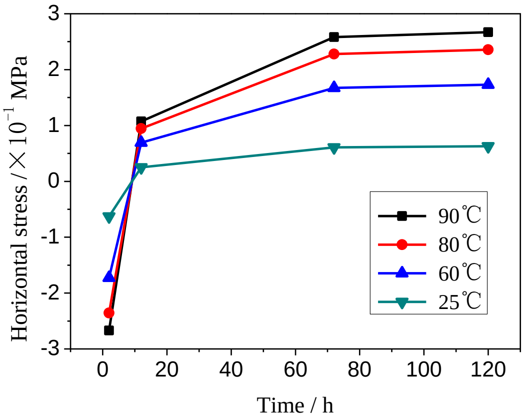

Figure 4. Horizontal stress curve of Point A.

Noting in Figure 3, for any selected determination point A, as the time passes, the variation of the temperature tends to be stable (x=0.187 m, y=-0.283 m) after 72 h. During the initial propagation (2~12 h) of the temperature, the temperature ramp of 90 ℃ is the largest for the surrounding rocks, and that of 25 ℃ is the smallest. As such, the temperature ramp of 90 ℃ is 4.25 times that of 25 ℃; and the temperature ramp of 80 ℃ and 60 ℃ is 3.75 times and 2.75 times that of 25 ℃, respectively. The temperature ramp rises as the temperature difference increases. During the period from 12~72 h, the temperature ramp tends to decrease. For the 90 ℃, the temperature ramp is only 7.26% of that during the period from 2~12h. The temperature ramp of the other three temperatures almost reaches approximately 7.45% on average of that during the period from 2~12 h. Over time, the temperature difference between the fracture and the surrounding rock tends to gradually approach balance.

Figure 4 shows the horizontal stress curve of point A that increases along with time under temperatures.

The horizontal stress generated by the surrounding rock at 90 ℃ is the largest. The stress at 90 ℃ concentration growth rate near the fracture is 4.3 times larger than that at 25 ℃. Temperature difference between the surrounding rock and the fracture decreases as the temperature of the surrounding rock decreases, and the magnitude of its stress also reduces accordingly. With the transformation of temperature, the stress concentration around the fracture weakens continuously and tends to stay at a stable temperature after 72 h.

4.2. Comparison of results

Taking partial segment 2# of the water diversion tunnel as the object, the data of the on-site temperature measurement for the fixed point of the tunnel segment is recorded by selecting the horizontal length of 1 m relative to the fracture, and a vertical distance of 1 m at the fixed point S. At the same time, numerical experiments can be conducted by using the computational model with the same conditions. The results are shown in Figure 5.

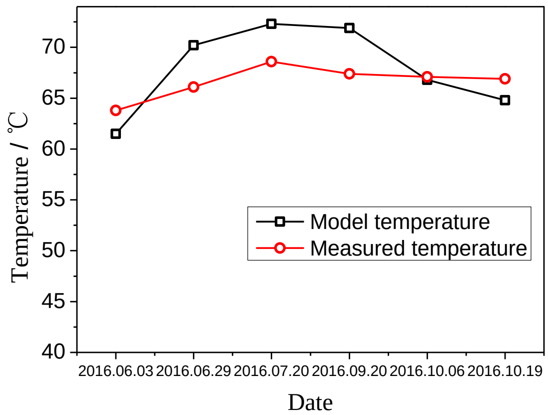

Figure 5. Comparison diagram of the actual measured temperature and the calculated temperature at point S.

It is evident from Figure 5 that the variation tends to be consistent between the actual measured temperature and the calculated temperature at point S. The maximum average temperature appeared at 1128 h of the computational model on the measurement date of 2016.07.20. The actual temperature descending ranges of 9.20~10.06 and 10.06~10.19 are 6.3 times and 5.0 times that of computational model, respectively. The actual temperature descending range of 10.06~10.19 (13 d) was reduced by 61% from 9.20~10.06 (16 d) within the same period. The reason is that the branch tunnel adjacent to the 2# tunnel segment is connected to the main tunnel after 9.20, so the air convection is strengthened through the exchange of air with heat from the external environment. However, the working condition during this period was not taken into consideration in the computational model.

5. Conclusions

The numerical experiments of the fractured rock mass at different temperatures indicate that the propagation of different temperature fields in the tunnel surrounding rock satisfies a certain fracture pattern and tends to stabilize after three days of heat transfer.

The surrounding rock stress concentration is positively correlated to the temperature difference between the high-temperature tunnel surrounding rocks. A greater temperature difference indicates greater rock instability, and when the fracture zone of the rock contains a large temperature difference, the surrounding rock is more prone to instability.

The numerical experimental results are consistent with the measured outcomes, which means that the development of the model has both a scientific and a practical value. The systematic numerical experiment can create a solid theoretical foundation for further engineering design.

Acknowledgments

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References

[1] Simpson C 1985 *Journal of Structural Geology* **18** 503–511
[2] Karel S and Bedeiich M 1996 *Journal of Structural Geology* **18** 719–733
[3] Alsha Y.N.A, Khan K and Abduljauward S. N 2000 *International J.of Rock Mechanics and Mining Sciences* **37** 629–643
[4] Dwivedi R.D, Goel R.K, and Prasad V.V.R 2008 *A Sinha Thermo-mechanical properties of Indian and other granites* **45** 303–315
[5] Noorishad J, Tsang C. F and Witherspoon P.A 1984 *J. Geophyte Res.***89** 165
[6] Li N , Xu B, Chen X.F 2006 *China Journal of Highway and Transport* **19** 1–5
[7] Bahr H. A, Balke H and Kuna M 1987 *Theoretical Applied Fracture Mechanics* 33–39